MERGING OF RECENT DEVELOPMENTS IN AVALANCHE SIMULATION TECHNOLOGY INTO PRACTICE

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ABSTRACT: Numerical simulations are essential for hazard mapping and mitigation measure planning in avalanche engineering. Avalanche experts rely on numerical models to study various hazard scenarios, investigating the influence of release zone location and dimension on runout distances, velocities and impact pressures in general three-dimensional terrain. However, new demands are arising from avalanche practice. Users wish to investigate avalanche-obstacle interaction, use the model to study the runout dynamics of small avalanches and understand the dynamics of wet and powder avalanches. In response, new numerical schemes have been implemented to improve the stability of the numerical calculations, especially in steep, rough terrain, including snowcover entrainment. The standard Voellmy model has been updated to include snow cohesion, which improves the prediction of the stopping behavior of dense snow avalanches. However, future applications will require fundamentally new physical models of avalanche flow. The next generation of numerical models is now in the testing phase. These models account for the granular and temperature dependent nature of snow avalanches. With these features it is possible to predict streamwise density variations in the avalanche core and powder cloud, improving predictions of avalanche impact pressure. As the temperature of the snowcover defines the thermal flow regime, wet snow avalanches can be simulated, including the lubricating role of melt water on avalanche runout. The new models, however, will require more detailed specification of the avalanche track and snow conditions. In this paper we present new features implemented in RAMMS and discuss upcoming novel model approaches including their limitations.

KEYWORDS: RAMMS, numerical simulation, hazard mapping, mitigation measure planning.

1. INTRODUCTION

The avalanche dynamics program RAMMS was introduced into Swiss avalanche practice in October 2010. Unlike many other European countries, avalanche mitigation in Switzerland is decentralized and depends on the knowledge of local avalanche experts. RAMMS was designed as a simple to use, avalanche-modeling tool that could be applied to study a wide range of mitigation problems by independent avalanche professionals. The numerical model runs on a single core personal computer, allowing engineering and land planning offices the possibility to investigate different avalanche hazard scenarios. The numerical program is accompanied by a user-friendly interface to facilitate the input of terrain, maps and initial conditions (Fig. 1). The price of RAMMS was set such that it was affordable to all engineering offices. Every year RAMMS user-workshops are conducted where examples are discussed to establish consistent, reproducible and transparent calculation procedures for avalanche dynamics calculations throughout Switzerland. RAMMS is also available to international users.

RAMMS has proven to be a valuable tool to support avalanche professionals, especially for the delineation of hazards maps. Hazard maps are based on extreme events, which can be well simulated using the standard Voellmy model (Christen et al., 2010; Salm et al., 1990; Voellmy, 1955). The prolific interaction with more than 200 users worldwide, has led to a list of new user demands. These include:

- Simulation of small and frequent avalanches
- Simulation of wet snow avalanches
- Simulation of powder avalanches
- Forest-avalanche interaction
- Inclusion of snowcover entrainment

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- Simulation of starting conditions, including artificial avalanche release and secondary avalanches
- Improved numerical stability in steep terrain
- Simulation of flow around houses, dams and obstacles
- Simulation of curved and twisted channels
- Improved stopping behavior with less numerical diffusion
- Reliable and transparent friction coefficients

In general, the demands from practice reveal that engineers are interested in more detailed numerical simulations for specific applications. For example, to simulate small and frequent avalanches threatening roadways and ski runs. Such problems often involve the interaction with forests, or the problem of snowcover entrainment.

Many of the user demands can be treated by updating the existing model. Other demands require introducing more precise physical descriptions of avalanche flow. In this paper, we present a number of RAMMS model improvements implemented to address user needs. These have been incorporated in the RAMMS user version 1.6.20. We also discuss extended avalanche dynamics models which are presently under development.These models cannot be implemented within the existing modules as they require entirely new parameter sets. The new model will form the basis for the RAMMS::EXTENDED avalanche module which will allow the simulation of powder and wet snow avalanches. However, any new model must be congruent to existing calculation procedures and thoroughly tested before widespread use on practical problems. As always, the goal must be to simplify avalanche mitigation and not confuse users with an increasingly complex simulation tools.

2. FOREST AND TERRAIN

2.1 Inclusion of forests

Forest areas are currently treated in RAMMS as regions with increased turbulent friction. This approach is based on calculations on the energy loss due to tree breaking, overturning and debris entrainment during avalanche-forest interaction (Bartelt and Stökli, 2001). Forest decelerates the avalanche but hardly shortens the runout distance. This approach is valid for avalanche events where extensive forest destruction takes place.

A new forest detrainment approach was developed to quantify the effect forest has on small to medium sized avalanches (Feistl et al., 2014). This approach is based on the assumption, that the avalanche does not destroy the forest. Trees act as rigid obstacles and oppose the avalanche flow. This extracts significant amounts of snow from the flow volume. The mass extraction per unit area is calculated with the detrainment function

$$\frac{dM_d}{dt} = -\frac{K}{|\mathbf{u}|} \qquad (1)$$

where $\mathbf{u}$ is the vector of mean slope parallel velocity $\mathbf{u} = (u, v)$ in the x and y-directions, respectively. Mass extraction is governed by the coefficient K [$kgm^{-1}s^{-2}$]. K varies according to the forest type, crown coverage and surface roughness. Dense, evergreen forests decelerate and stop avalanches more efficiently than open forests with smooth soil surface. Different forest structures can now be applied and their effect on small to medium sized avalanches can be quantified (Fig. 1).

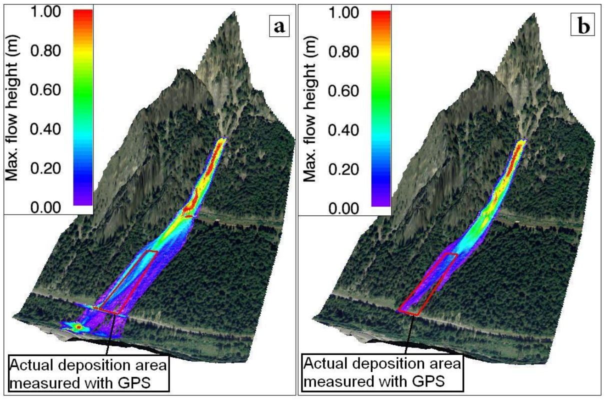


Fig. 1. RAMMS simulation of a forest avalanche near Filisur, Switzerland. Simulations with the friction approach (a) and detrainment approach (b).

2.2 Centripetal pressures

The normal pressure N includes centripetal pressures N_f arising from the terrain curvature. To calculate N_f we must determine the centripetal accelerations f_z, $N_f = M_\Phi f_z$, where M_Φ is the mass of the avalanche flow column. This is somewhat complicated as the centripetal accelerations are a function of both avalanche velocity and terrain curvature. Terrain curvature depends on the spatial resolution of the digital elevation model We use a spatial second-order method proposed by (Fischer et al., 2012). The centripetal acceleration f_z is defined as

$$f_z = \mathbf{uKu}^T . \tag{2}$$

The matrix $\mathbf{K}$ is a 2x2 matrix defined for every cell in the model domain that describes the curvature in x, y and xy- directions. The quadratic form supplies the velocity squared terms in the acceleration. The xy-direction describes the track “twist”.

Because of the generally concave track curvature, centripetal accelerations will increase the normal pressure N and therefore the Coulomb shear stresses, causing the avalanche to slow down in tortuous and twisted flow paths. Curvature effects can also modify the direction an avalanche exits a flow gully, leading to different deposition behavior.

The study area Albertitobel is located above Davos in the eastern Swiss Alps. It is a well-known avalanche path with the release area situated at 2100-2400 m above Davos Platz (1560 m). The release area consists of two connected slopes ending in a narrow channel that continues to the village. Fig. 2 shows the simulated maximum velocity of the Albertitobel avalanche calculated without curvature effects. The avalanche overflows the ridge towards Lochalp. If we apply curvature effects to the simulation the overflow disappears. In this example the avalanche calculated without curvature hits the building at Lochalp (black circle) and the simulation calculated with curvature misses this building. The simulated avalanches tend to stay longer in channels if the curvature effects are included. This is an indication that numerical simulations without curvature effects tend to be more conservative. However, in most cases including curvature effects leads to more realistic simulation results in particular in twisted flow paths.

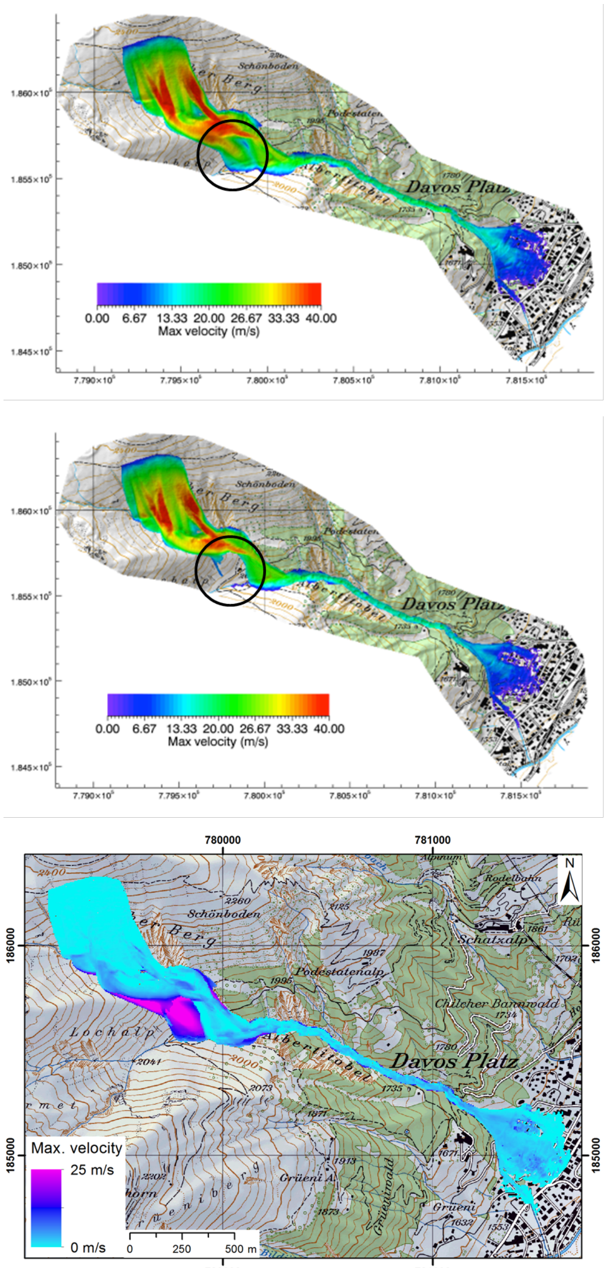


Fig. 2. Maximum velocities of the Alberti avalanche calculated without curvature (top), with curvature (middle) and the difference image between the two simulations (bottom).

3. IMPROVED NUMERICAL CODING

3.1 Numerical scheme

RAMMS employs second-order Runge-Kutta time integration methods couple with second-order ENO (Essentially Non-Oscillatory) spatial discretization scheme to numerically solve the governing differential equations (Christen et al., 2010). The equations are solved in conservative form and thus the physical quantities of mass and momentum are conserved exactly. The first version of the numerical solution scheme, however, was implemented on strictly orthogonal grids in the x-y plane. This improves computational speed, but introduces numerical instabilities especially in steep and rough terrain. The new version of RAMMS uses the same second order ENO scheme, but now on general quadrilateral grids defined with respect to the surface manifold. This new scheme improves numerical stability, but slows the computational speed. The introduction of this procedure allows us to use lower height cut-offs values minimizing mass loss during calculations. The standard value of the height cutoff is now 1 μm.

3.2 No-flux boundary conditions

Hazard assessment requires defining regions where the flow is blocked. Such areas could be dams, obstacles, edges of steep gullies or even buildings. A no-flow region can be defined by drawing a shapefile in RAMMS and defining it as a "no-flux" boundary condition. An automatic routine fines the cell edges where the boundary condition is imposed. A rounded region is therefore approximated by a series of strait cell edges. Friction can be introduced at an edge to take into account energy dissipation during the impact and deflection.

To demonstrate the effects of no flux boundary conditions we present an example from Davos where numerous buildings in the run out zone are likely to influence the stopping behavior and the path of the avalanche (Fig. 3). In February 1984 the Albertitobel avalanche released and reached the first buildings of Davos damaging three buildings and killing three persons (Spichtig and Bründl, 2008). To control the amount of available snow in the release area an avalanche control system has been installed.

By setting the building areas as no flux cells we assume that the avalanche destroys no buildings and that the flow is channeled around the buildings. This is not realistic because at least the first row of the buildings is likely to be destroyed and overflown by the avalanche. However, calculating the avalanche without buildings does not account for potential flow deflections. In such cases it might be helpful to calculate scenarios with and without buildings as no flux cells to assess potential effects on avalanche run out.

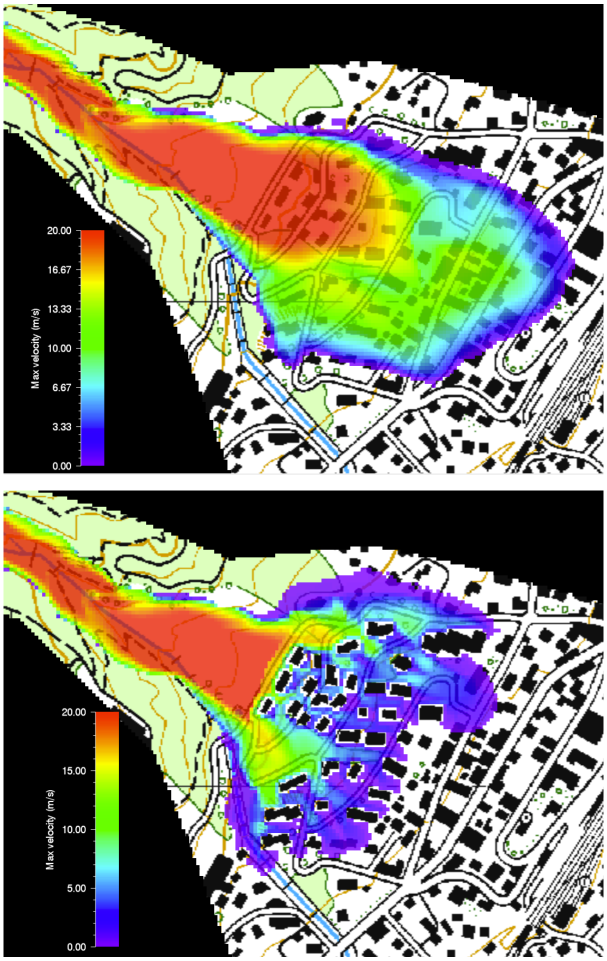


Fig. 3. RAMMS simulation of the Alberti avalanche in Davos, Switzerland without buildings (top) and with buildings as no flux cells (bottom). All other model settings are constant.

4. SNOW COHESION

A problem with numerical simulations is to define the exact stopping position of an avalanche. Numerical solutions often diffuse with low velocity and low flow height. The diffusion can add several 10s of meters to the predicted avalanche width and runout.

To remedy this problem we introduced cohesion as an independent model parameter into the Voellmy friction law. Cohesion leads to material bulking and prevents diffusive like runout behavior. It lessens the flow width of avalanches and, in general, decreases avalanche runout. It increases avalanche deposition heights, producing steep pile-ups in flat terrain sections.

In RAMMS we treat snow cohesion as (1) an additional potential energy that must be overcome to "pull-apart" and break cohesive bonding between snow granules and (2) a normal stress independent shear stress that modifies the Coulomb friction (Bartelt et al., 2014). Both the potential energy and shear stress are defined by one parameter, N_0. The dimensions of N_0 are either pressure Pa, or specific energy density J/m3.

The cohesion model in RAMMS was developed from shear and normal force measurements in real snow flows at the SLF experimental snow chute (Platzer et al., 2007a; Platzer et al., 2007b). These experiments showed an essentially linear relationship between the normal force N and shear stress S. Often, however, the experimental measurements showed a strong increase in shear before the linear relationship between shear stress S and normal stress N could be established. This initial perturbation in the shear response was assigned to the effects of cohesion. In order to reproduce the experimental results we modified the standard Voellmy shear stress model,

$$S = \mu N + \frac{\rho g \|\mathbf{u}\|^2}{\xi} \qquad (3)$$

to

$$S = \mu N + (1-\mu)N_0 - (1-\mu)N_0 \exp\left[\frac{N}{N_0}\right] + \frac{\rho g \|\mathbf{u}\|^2}{\xi} \qquad (4)$$

This relation ensures that many of the measured features of the shear stress are reproduced, for example $S \rightarrow 0$ when both $N \rightarrow 0$ and $\|\mathbf{u}\| \rightarrow 0$. The formula increases the shear stress and therefore causes the avalanche to stop earlier, depending on the value of N_0 (Fig. 4).

Table 1: Proposed snow cohesion for dry and wet snow avalanches.

Avalanche type	*Cohesion [Pa]*
Dry	0 - 100
Wet	100 - 300

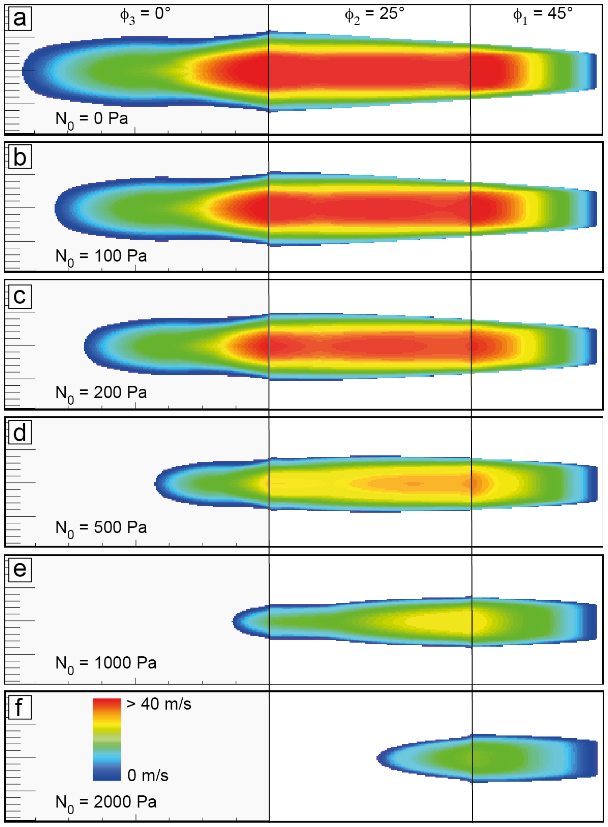


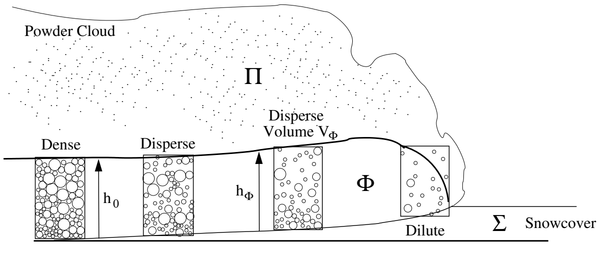
Fig. 4. Effect of snow cohesion on the runout distance and velocity on an idealized surface. Taken from(Bartelt et al., 2014 (submitted)) .

5. NEW AVALANCHE DYNAMIC MODEL

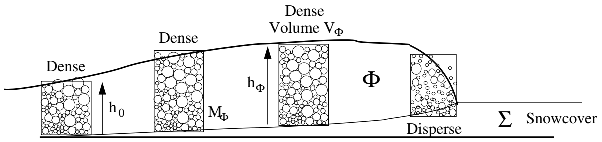
Snow avalanches are divided into dry and wet, depending on the moisture content of the snow cover. The dynamics of dry and wet snow flows differ considerably from each other. Dry avalanches form from dry, cold snow, move up to speeds of 80 m/s and usually develop a powder cloud which can attain several hundred meters in height. Wet snow avalanches form from dense, moist snow and have evident visco-plastic properties. In comparison to dry avalanches they move relatively slowly (10-20 m/s). However, because both flow regimes propagate long runout distances and can exert large forces on obstacles, the two flow regimes have been traditionally lumped into a single category, independent of the snow temperature. Avalanche calculations have typically assumed a single "generic" flow type, independent of the snow properties.

The new extended version of RAMMS, currently under development and testing at SLF, will allow users to investigate avalanche runout in different climatic elevations and regions (e.g. wet maritime or dry continental). Users will be required to specify snow density, temperature and moisture content in the release zone. For example, for a dry avalanche a new snow density of ρ = 200 kg/m^3, T = -10° C and zero moisture content could be specified whereas for a wet avalanche a density of σ = 400 kg/m^3, T = 0° C with some initial moisture content could be defined. The temperature of the release zone, as well as the temperature of the entrained snow cover, then determines the avalanche flow regime. The temperature of the snow can be constant, or increase as a function of the elevation.

Flow regime and flow regime transitions (Fig. 5) are modeled by extending the governing equations to include for (1) streamwise density variations in the avalanche core, (2) the thermal heat arising from dissipation of mechanical energy and entrainment and, finally, (3) lubrication effects leading to enhanced avalanche gliding.



a. Mixed flowing avalanche



b. Dense flowing avalanche

Fig. 5. Avalanche models will account for the streamwise density variations and will model both mixed flowing/powder and dense flowing avalanche type (Buser and Bartelt, 2014 (in revision))

5.1 Fluidization of dry snow avalanches

Fluidization of dry snow is the result of dispersive pressures N_k arising from granular interactions with the basal running surface. When dry snow particles hit the basal boundary, they are reflected back into the flow. These particles in turn hit other particles, causing a net change in the center-of-mass of the flow core k_Φ. Considering, for example, snow clods and fragments that are accelerated to significant heights in the air. These heights define the flow height of the avalanche. The RAMMS model solves the differential equation:

$$M_\Phi \dddot{k}_\Phi + M_\Phi \left[g_z + f_z + \ddot{k}_\Phi \right] \frac{\dot{k}_\Phi}{k_\Phi} = \dot{R}_V \qquad (6)$$

where M_Φ is the mass in an avalanche flow column; g_z is the gravitational acceleration in the slope-perpendicular direction and $\dot{R}_V$ is change in potential energy from the granular interactions with the boundary (Bartelt et al., 2011). The quantity $\dot{R}_V$ is calculated from the frictional shear work in the slope parallel direction (Bartelt et al., 2006).

The total force “pressing” against the ground includes the avalanche weight $N_g = M_\Phi g_z$, the pressure from centripetal accelerations $N_f = M_\Phi f_z$ and the dispersive pressure $N_k = M_\Phi \ddot{k}_\Phi$:

$$N = N_g + N_f + N_k \qquad (7)$$

The dispersive pressure accounts not only for such particle ejections but also for their downward return. It is therefore related to changes in granular positions (configuration) and the transfer of energy from the slope-parallel flow direction to slope-perpendicular movements in the avalanche core. These changes in granular positions are clearly a function of the mechanical and thermal properties of the snow granules. A significant result is the change in avalanche flow density. Fluidization leads to disperse, intermittent flow fronts associated with dry flow regimes. Impact calculations are based on streamwise variations in bulk avalanche flow density.

5.2 Lubrication of wet snow avalanches

RAMMS::EXTENDED explicitly calculates the bulk avalanche flow temperature from initiation to runout. The temperature and density of the snow mass in the release zone account for the initial internal heat energy of the avalanche. The internal heat energy increases with the dissipation of kinetic energy in the slope parallel direction (frictional work). This can increase the temperature of the avalanche core by several degrees. Another mechanism to increase the internal energy is by the dissipation of the kinetic energy associated with random particle trajectories. This is a secondary, and perhaps minor, contributor of internal energy. The major influence on the thermal flow regime, however, is the temperature of the entrained snow. In fact, recent investigations (Steinkogler et al., 2014; Vera Valero et al., 2012) determined that entrained snow can increase the temperature by more than the several degrees. An avalanche can start at T_0 = -10° C and if it entrains enough warm snow (T = 0° C) can begin to change the phase of the snow clods composing the avalanche core.

When the avalanche warms significantly, meltwater is created in the regions of largest frictional working; that is, the surface of the snow granules which much endure both plastic collisions and consistent shearing and rubbing. At first this will increase the cohesion (see section 4) between granules. As the granules stick together more easily, granule size increases. However, if the excess heat produces enough melt water, the melt water begins to reduce the shear strength of the snow and lubricate frictional surfaces. This facilitates the formation of smooth gliding surfaces, leading to extreme runout of wet snow avalanches. The avalanches move slowly, but far. The flows are dense and plug-like because the granule properties prevent the fluidization of the avalanche.

Meltwater production (and therefore lubrication) varies in the streamwise flow direction. Typically, the onset of melting occurs after the front passage. The temperature of the front appears to be controlled by the temperature of the entrained snow and not by dissipative processes. Subsequently, lubrication appears in the avalanche bulk, leading to the formation of deposition structures such as levees and shear planes which reflect both the cohesive and lubricating processes of avalanche warming.

Presently, work is underway to develop “lubrication relations” that account for the reduction in friction as a function of the bulk meltwater content of the avalanche.

6. CONCLUSIONS

User feedback from avalanche engineers and land planners has identified several problems that require improvements. The feedback has underscored the increasing importance of numerical simulations in avalanche practice. Most of the problems require a more detailed physical description of the flow. These include: cohesion, centripetal accelerations, entrainment, density variations, interactions with obstacles and the role of snow temperature in defining the friction parameters. Numerical stability has been improved.

The danger of introducing new physical processes is manifold. For one, new parameters are introduced into the hazard analysis. The values of these parameters are based on isolated events that may not represent the full range of avalanche behavior. Model calibration and validation remains a major challenge in avalanche dynamics.

A key component to the application of numerical methods will be user education. Workshops have the goal of establishing consistent and transparent calculation procedures based on user applications. User demands lead to more complex numerical simulations which are outside the scope of existing calculation guidelines. The guidelines are presently based on extreme avalanches without entrainment and therefore require only a subset of the new developments and input parameters. This situation will remain in place for years to come, but special hazard scenarios (e.g. small avalanches) will require the application of new methods.

Time will be required to test all the new model developments and judge their value for practical application. One advance induced by the new developments is already apparent: there is a tremendous benefit from fieldwork where avalanche events are documented in detail. Documentation of avalanche events – large and small, in different snow conditions and temperatures – can be used to establish reliable and consistent model parameters.

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